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Development of glacier mapping in Indian Himalaya: a review of approaches

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ABSTRACT

The paper reviews the status of glacier mapping with special reference to the Indian Himalaya. The review provides information on various satellite remote sensing data interpretation methods used with special emphasis laid on recent semi-automated algorithms used for glacier and debris-cover mapping, along with their limitations and challenges. Further, the pragmatic solutions on offer are discussed, and the emerging areas of glacier mapping research are highlighted. The review also touches – contribution of Survey of India (SOI) and Geological Survey of India (GSI) in the glacier mapping. Finally, it discusses the wider range of spatial and spectral domains in which remote sensing data helps to inventories glaciers. The review also identifies gaps in using the latest techniques like Unmanned Aerial Vehicles (UAVs) and machine learning algorithms to improvise on the ongoing efforts. At last, the review provides an exhaustive list of references on glacier mapping from the Indian Himalaya as benefit to readers.

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1. Introduction

1.1. *Rationale of the glacier mapping*

In order to examine the earth surface dynamics and landscape evolution through time, mapping of landforms and surface features by means of remote sensing and/or fieldwork is a well-established practice in Earth Sciences (Chandler et al. 2018). Among these, mapping of glaciers bears great significance as these are known proxy for global climate change (Oerlemans 2005). The glacial extent is a primary input for most of the glaciological studies and numerous hydrological modelling (Shukla 2009). Precise information about the extent and distribution of glaciers is needed for many other research applications, e.g. water resource management, mitigation of glacial hazards and estimation of the past and the future contributions of glaciers to sea-level change (Rastner et al. 2014). To represent spatial morphology of glaciers on the map is the principal objective of glacier mapping (Bhambri and Bolch 2009). Traditionally, 'direct' glaciological methods were used to estimate the

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glacier mass balance, whereas the increased availability and improved quality (spatial and spectral resolution) of satellite imageries allow fast and cost-effective monitoring of glacier parameters. Moreover, using recent geospatial tools (e.g. remote sensing, Digital Image Processing (DIP), Geographic Information System (GIS) and spatial data integration and modelling), 2D/3D mapping of glacier terrain is possible for better visualization (Bolch, Menounos, and Wheate 2010). Satellite data has made it possible to observe glacier characteristics that were difficult to measure using ground-based method (Paul et al. 2015). Using these techniques numerous studies have reported the status of glacier characteristics at different times and on different scales (Paul, Kääb, and Haeberli 2007; Bajracharya, Maharjan, and Shrestha 2014; Kulkarni et al. 2011; Thakuri et al. 2014; Pandey and Venkataraman 2013; Bahuguna et al. 2007; Kaushik et al. 2018). Geographical extent and terminus position of glaciers are the widely used parameters to assess the overall health of the glaciers. In the last decade, significant improvement in satellite image resolution, evolution of Synthetic Aperture Radar Interferometry (InSAR), Light Detection and Ranging (LiDAR), locally controlled remote sensing systems (UAVs, Drones) and Digital Image Processing (DIP) algorithms have provided an opportunity for estimation of various glacier parameters. The advancements have led to the estimation of glacier surface elevation change (Dobhal and Mehta 2010; Rankl and Braun 2016), equilibrium line altitude (Garg et al. 2017; Rabatel, Dedieu, and Vincent 2005; Rabatel et al. 2013), debris cover (Robson et al. 2015; Shukla, Arora, and Gupta 2010; Racoviteanu and Williams 2012), surface ice velocity (Kumar, Venkataramana, and Høgda 2011; Scherler, Leprince, and Strecker 2008; Satyabala 2016; Rao, Venkataraman, and Rao 2004) and ice volume change (Surazakov and Aizen 2006; Miller et al. 2009). Such studies employing a multi-parametric approach have gained importance as they provide a comprehensive picture of glacier health. Historical development of Himalayan glacier mapping is well-documented by Raina and Srivastava (2008) and Bhambri and Bolch (2009). However, the present review is the first attempt devoted to the development in the algorithms and approaches for glacier mapping in the Indian Himalaya.

1.2. *Himalaya and climate change*

The Himalaya has the largest glacier coverage and seasonal snow outside the polar region. Accordingly, it is commonly referred as the 'third pole' (Bajracharya and Shrestha 2011; Dyhrenfurth 2011). Owing to this, Himalaya is a source of freshwater to a large proportion of the population across south and central Asia (Figure 1). Therefore, the Himalaya is one of the main driving force of economic development in downstream regions, as it provides extensive opportunity for irrigation, hydroelectricity and eco-tourism. Apart from being the water provider, the Himalayan glaciers and snow also influence atmospheric circulation, energy balance and subsequently regulate climatic changes of the Indian Sub-continent. The response of Himalayan cryosphere towards climate change can be seen as a glacier recession and overall loss in the frozen part of the region. Several studies report the alarming rate at which glaciers are retreating across the Indian Himalaya (Kulkarni et al. 2005, 2011, 2007). One of the most striking features in the Indian Himalaya can be seen as a result of glacial retreat is the evolution and expansion of glacial lakes due to the recent accelerated atmospheric warming. Due to such rapid recession of glaciers, associated catastrophic events such as glacial lake

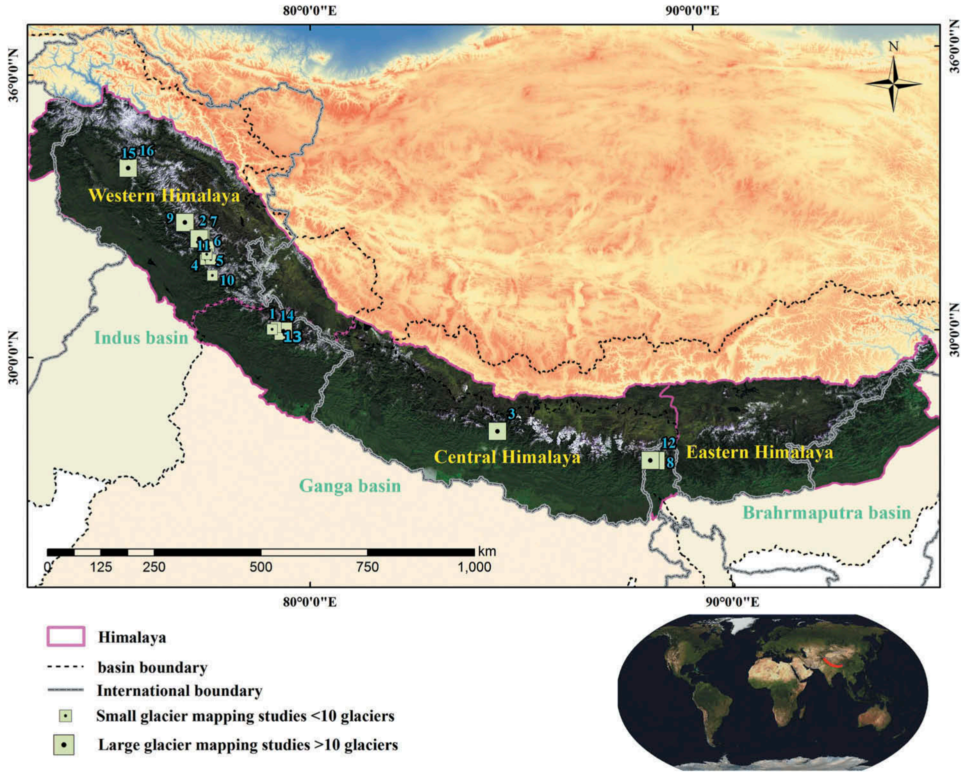

Figure 1. Overview of glacier mapping studies in Himalaya.

outburst flood (Bajracharya, Mool, and Shrestha 2007), avalanche, rockfall and water scarcity in the upper Himalaya villages are commonly reported (Kulkarni et al. 2002; Kulkarni 2007). Although Mass balance studies across the Himalayan glaciers are limited (Mukherjee et al. 2018; Brun et al. 2017; Kääb et al. 2012), most of these studies have primarily focused on the fluctuation of the glacier area and terminus (Table 1). In order to understand the regional climate, mitigate glacial hazards, water resource planning and predicting the future availability of water, it is indispensable, therefore, to study and monitor the Himalayan glaciers precisely. Due to the presence of glacier in remote and inaccessible mountain terrain (Paul et al. 2015), the geospatial techniques offer the advantage of synoptic view with repeat coverage in a cost-effective method for monitoring of glaciers. These advantages outweigh the field-based conventional methods that require enormous time, capital investment and involve huge manpower which is exposed to enormous risks.

1.3. *Aim of the present study*

The objective of this article is to provide a review of the development of glacier mapping in the Indian Himalaya with particular emphasis on the recent advances and development of automated and semi-automated approaches/algorithms towards the delineation of debris cover glaciers. Further, the challenges, limitations, and recommendations on glacier mapping using remote sensing data are discussed in detail. Moreover, the emerging area of glacier mapping with special reference to Indian Himalaya are discussed.

2. Brief history of glacier mapping in Indian Himalaya

Antonio Monserrate, a Spanish missionary to the court of the Mughal emperor Akbar presented the first known sketch map of the Himalaya in 1590 (Himalayas – Study and exploration; Encyclopedia Britannica 2019). Subsequently in 1733, a French geographer, Jean-Baptiste Bourguignon d'Arvilleprepared the first map of Tibet and the Himalayan range based on systematic exploration (Himalayas – Study and exploration; Encyclopedia Britannica 2019). Later, since its establishment in 1767, the Survey of India (SOI) is involved in surveying and mapping of Himalayan glaciers. The record of the earliest study conducted for movement of glacier terminus can be traced to 1812 for Chong Kumdam (Ullah 1843; Mayewski and Jeschke 1979) and Milam glaciers (Mayewski and Jeschke 1979; Hodgson 1822). Field-based surveying methods, especially plane table survey contributed notably to the glacier mapping of the Himalayan region. For example mapping of Mustakh range (Godwin-Austen 1864), Conway's journey to the Hisper glacier in 1892 (Conway 1893), numerous expeditions of Visser for Pasu and Batura glaciers and Mason expedition to Shaksgam (Mason 1927; Shipton, Spender, and Auden 1938) set the initial standards of comprehensive glacier studies. The flaw in the surveyed map of the glacier prepared by Godwin-Austen (1864) was reported by several studies (Longstaff 1908; Visser 1926). Based on the historical records, photographs and notes (Mason 1930) reported the status of 34 glaciers in Karakoram range and summarized notable glacier variations as secular (long-term), periodic (short term), seasonal and accidental (Mayewski and Jeschke 1979). Mason (1930) advised training is required for surveyors in recognizing glacier features and landforms. Additionally, he proposed colour schemes and guidelines for mapping of glacio-geomorphic features on the SOI maps. In 1932, Gilbert studied Arwa valley glaciers presently situated in the Chamoli district of Uttarakhand (Gilbert and Auden 1935). Visser and Visser-Hooft (1938) reported the state of 72 selected glaciers from the Karakoram Range. Most of their results were drawn from (Mason 1927, 1930) and the expeditions carried out in 1922, 1925, 1929–1930 and 1935. This study advocated that glaciers of Karakoram Range were advancing in 1900–1910 and retreating in 1910–1920. A study by Mercer (1963) also exhibits glacier fluctuation of 50 glaciers, 43 from Karakoram and 7 from Nanga Parbat and categorized them as steady, cyclic and catastrophic (Mayewski and Jeschke 1979). Tewari (1971) reported variation of 17 glaciers from Himalaya and Trans Himalaya. He highlighted that in general glaciers of Himalaya are retreating with varying rates while some glaciers in the Trans Himalaya showed remarkable advancement (Mayewski and Jeschke 1979), which is presently known as the 'Karakoram anomaly'. These studies focused on the correction of the earlier Himalayan glacier maps with advanced techniques and attempted to study glacier fluctuations.

Comprehensive historical information about the extent of the Himalayan glaciers can be traced back to the topographical map of 1960 prepared/published by the SOI using aerial photographs and limited field observation at 1:50,000 scale. Several studies reported accuracy issues in these SOI maps specifically in the case of the debris-covered glaciers (Vohra 1980; Agarwal 2001; Bhambri et al. 2011b; Raina 2009). Studies based on the SOI maps have reported a higher rate of retreat and loss of glacier than actual owing to the excess length of glacier represented in the SOI maps (Kulkarni et al. 2011). Earlier discrepancies in the SOI maps were highlighted by Mason (1929). The Geological Survey of India (GSI) initiated programmes to investigate the movement of glaciers, as part of the Commission internationale des glaciers during 1906–1908. This programme aimed to study 12 principal glaciers in Kumaun, Kashmir, and Lahul regions in order to prepare plane table glacier sketches (Sangewar 2012).

3. Glacier mapping using remote sensing and GIS

The proliferation of satellite imageries with the advent of Landsat programme in 1972, advancements in Global Positioning System (GPS) and emergence of Geographic Information System (GIS) showed a great potential for glacier mapping and monitoring (Gao and Liu 2001). This development was undoubtedly the most significant in the history of glacier mapping, as data from various sources can be incorporated in the GIS environment. Further, advancement in technology helped to revolutionize our understanding of the past glacier dynamics. Accordingly, the glacier mapping using remote sensing data broadly involves two approaches manual and automated delineation of features. Therefore, this paper first reviews the mapping of clean ice glaciers using manual and automated methods, further mapping of debris cover glaciers is discussed separately in Section 3.2.

3.1. *Manual delineation*

Initially, delineation of glacier boundary started with the manual digitization on standard false colour composites (FCC) of Landsat MSS imageries. This method is labour intensive and needs excessive time. Owing to the subjectivity involved in the method, it introduces human error as recognition of glacier terrain feature on satellite imageries may differ from analyst to analyst based on the individual's visual interpretation. Therefore, the accuracy of this method depends on the expertise of the image analyst and scene characteristics (e.g. seasonal snow, clouds and shadow). This method incorporates a standard combination of spectral bands (e.g. SWIR, R, G) aided with image enhancement techniques (e.g. contrast enhancement) and DEM derived parameters (e.g. Slope) which help to differentiate between glacial and non-glaciated surfaces. For accurate identification of glacier terminus and extent, an association between geomorphic features such as the presence of moraine-dammed lakes and steep ice wall at terminus play key role. For this purpose, satellite imageries of the ablation period (e.g. September) with minimum cloud are considered most suitable (Pandey and Venkataraman 2013). The manual delineation of the glacier is still in practice though laborious, it has a high degree of accuracy especially when high accuracy is required (Albert 2002; Garg et al. 2017).

The glacier inventory of Indian Himalaya was carried out using on-screen manual digitization on standard FCC of satellite imageries (e.g. Landsat multispectral scanner (MSS) and Indian Remote Sensing Satellite (IRS) LISS I/II) aided with SOI topographic sheets by Kulkarni (1991), Kulkarni and Buch (1991), Dobhal (1992) Dobhal and Kumar (1996), Kulkarni et al. (1999), Dhanju and Buch (1989), Kaul (1999). Several studies made significant contributions and set the momentum for Himalayan glaciers studies in India (Dobhal, Kumar, and Mundepi 1995; Kumar and Dobhal 1994; Dobhal and Kumar 1997;

Mourya et al. 2002; Kulkarni 1993). The Space Application Center (SAC) completed a glacier inventory for the entire Indian Himalaya at a scale of 1:250,000 in the early 1990s (Bahuguna 2008). Table 2 summarizes some significant studies carried out to investigate the glacier status in Indian Himalaya using manual digitization method.

3.2. *Automated delineation*

With the development of DIP techniques (i.e. computational techniques) and improved image resolution (i.e. spatial and spectral), automated delineation of glacier boundary gained importance in order to facilitate fast and accurate glacier mapping. Band ratio methods (e.g. Normalize Difference Snow Index (NDSI) and single band ratio) emerged as the most competent method for glacier delineation (Kääb et al. 2002; Shangguan et al. 2006; Albert 2002). These methods are fast, accurate and robust with high reproducibility of results. The automated delineation of clean ice glacier relies heavily on the high reflectivity of snow and ice in the visible and near-infrared region wavelength compared with very low reflectivity in the shortwave infrared (Figure 2) (Li et al. 2013b; Bhardwaj et al. 2015; Racoviteanu et al. 2009). Several studies reported delineation of clean ice glacier using above-mentioned techniques (Racoviteanu et al. 2009; Bhardwaj et al. 2015; Bhambri, Bolch, and Chaujar 2011a; Krishna 2005; Frey, Paul, and Strozzi 2012; Paul and Kääb 2005). Further, these studies suggested slight modifications in the threshold of band ratio according to the scene characteristics (e.g. topography, sun position, and haze). The NDSI algorithm is applicable to differentiate clean to slight dirty ice from surrounding bedrock owing to its dissimilar spectral signature.

However, in the presence of shadow and/or clouds and/or seasonal snow and/or creeping feature in cold dry region, this remains a challenging task (Frey, Paul, and Strozzi 2012). Furthermore, spectral response of supraglacial debris (SGD) present on the glacial surface and periglacial debris (PGD) occurring outside glacier boundary is indistinguishable in reflectance region being derived from a common source (Shukla, Arora, and Gupta 2010) (Figure 3). Therefore, their discrimination is impossible with optical remote sensing, alone. Hence, approaches and methodologies are required to map debris-covered glaciers. These are discussed in Section 3.2.

Table 1. Overview of some significant studies shown in Figure 1.

S. No.	Author	Study area
1	Bhambri et al. (2011b)	Alaknanda basin, Gharwal Himalaya
2	Bhardwaj et al. (2014)	Patsio glacier, Himachal Himalaya
3	Robson et al. (2015)	Mansalu region, Nepalese Himalaya
4	Bhardwaj et al. (2014)	Hamtah glacier, Himalchal Himalaya
5	Kulkarni et al. (2006) and Shukla et al. (2010a)	Samudra Tapu glacier, Himalchal Hiamalya
6	Pandey and Venkataraman (2013)	Chandra-bhaga basin, Himachal Himalaya.
7	Racovitneau et al. (2014)	Kanchenjunga, Sikkim Himalaya
8	Garg et al. (2017)	Chandra basin, Himachal Himalaya
9	Kulkarni et al. (2011)	Miyar basin, Himachal Himalaya
10	Kulkarni et al. (2005)	Parbati glacier, Himachal Himalaya
11	Dhobal et al. (1995) and Garg et al. (2017)	Chhota-shigri glacier, Himachal Himalaya
12	Basnett et al. (2013)	Tista basin, Sikkim Himalaya
13	Bhambri et al. (2011a)	Gangotri glacier, Garhwal Himalaya
14	Bhambri et al. (2011a)	Chorabari glacier, Garhwal Himalaya
15	Shukla and Ali (2016)	Kolahoi glacier, Kashmir Himalaya
16	Murtaza and Romshoo (2017)	Lidder valley, Kashmir Himaalaya

Table 2. Summary of some significant glaciers studies carried out in Indian Himalaya using manual digitization method.

Location	Data Used*	Results	Brief description	Reference
Parbati-Spiti basin, Himachal Pradesh	Landsat TM (30 m)		Delineated with FCC of bands 2 (Green), 3 (Red), 4 (SWIR) and error in estimation of glacier parameter was not incorporated.	Dhanju and Buch (1989)
Himachal Himalaya	Landsat TM (30 m)	125 glaciers were mapped on 1:250,000 scale.	Delineated on FCC and toposheets.	Kulkarni (1991)
Himachal Himalaya	Landsat TM (30 m)	601 glaciers were mapped in 6 drainage basins on 1:25,000 scale.	Delineated on FCC and toposheets.	Dobhal and Kumar (1996)
Baspa basin, Himachal Pradesh	IRS LISS II (23.5 m)	30 glaciers mapped in the basin; further 19 were selected to estimate retreat.	Historic extents of glaciers were mapped using SOI topographic maps (1:50,000 scale). For the year 2001 mapping was done using FCC aided with image enhancement techniques.	Kulkarni and Alex (2003)
Parbati glacier, Beas basin, Himachal Pradesh	Landsat TM (30 m) IRS LISS II (36.25 m) IRS Pan (5.8 m) and LISS III (23.5 m) SOI topographic maps	Reported retreat of parbati glacier with 52 m/yr between 1990 and 2001.	Delineated on SOI topographic maps and then overlaid on temporal satellite imageries for estimation of retreat. The study does not incorporate error involved in the estimation of glacier parameter.	Kulkarni et al. (2005)
Samudra Tapu glacier, Chandra-Bhaga basin, Himachal Pradesh	IRS LISS II (36.25), IRS PAN (5.6) LISS III (23.5 m) SOI topographic map	Samudra Tapu glacier retreated 742 m (19.5 m/yr) between 1962–2000.	Delineated on SOI topographic map and change in extent and terminus retreat was estimated using multi-temporal remote sensing data.	Kulkarni et al. (2006)
Himachal Himalaya	IRS LISS III (23.5 m) IRS LISS IV (5.6 m) SOI topographic map	466 glaciers extent were delineated using topographic maps and satellite images. This study reports 21% loss in glacier area between 1962–2004.	The overestimation of glacier fluctuation is attributed to discrepancies in the SOI topographic maps.	Kulkarni et al. (2007)
Tista, Gori Ganga, Bhagrithi, Baspa, Parbati, Chandra, Bhaga, Miyar, Bhut, Warwan, Zanskar	WiFS (188 m) AWiFS (56 m) LISS III (23.5 m) LISS IV (5.6 m)	Tabulated status of 1868 glacier distributed in 11 sub-basin of Indian Himalaya since 1962.	Delineated using on-screen manual digitization in GIS environment on topographic maps and time series satellite imageries. The overall deglaciation of 16% was reported.	Kulkarni et al. (2011)
Chandra-Bhaga, Himachal Himalaya	Landsat MSS (83 m) Landsat TM (28.5 m) IRS LISS III (23.5 m) AWiFS (56 m)	15 glaciers were delineated using time series remote sensing data. Overall 2.5% of deglaciation was found in the study.	Error involved in the in the estimation of glacier area and retreat is incorporated (1.5–4%). Reported rate of deglaciation is quite lower to previously reported rate because this study excluded the use of SOI topographic maps.	Pandey and Venkataraman (2013)

(*Continued*)

Table 2. (Continued).

Location	Data Used*	Results	Brief description	Reference
Chandra basin, Himachal Himalaya	Landsat TM (30 m) Landsat ETM (30 m) Landsat OLI (30 m) World View2 (0.52–2.4 m)	Study reported Sakhchum and BaraShigri retreated (10.65 ± 2.52 m/y; 15.51 ± 2.52 m/y) the Chhota Shigri remained relatively stable (retreat rate: between 1993–2014.	Delineated of glacier boundary on medium resolution data owing to its high accuracy than any other method. Study also quantized the uncertainty/error involved in estimation of glacier parameters.	Garg et al. (2017)
Indus, Ganga and Bharmputra basins.	Resourcesat-1 AWiFS (56 m)	Study showed total glacier of 71,182 km^2 in 32,392 glaciers.	On-screen visual interpretation technique utilizing input from optical and topographic remote sensing data for glacier mapping.	Kääb et al. (2012)
High mountain Asia	Landsat ETM+ (30)	This shows the presence of 87,084 glaciers with a 91,263 ± 13 689 km^2 area, throughout high-mountain Asia.	A new glacier inventory for high mountain Asia. Glacier boundary was delineated using 356 Landsat ETM+ scenes in 226 path-rows, aided with a DEM and high-resolution Google Earth imagery.	Nuimura et al. (2015)

Note: *Values in the parenthesis is a spatial resolution of remote sensing sensor.

AWiFS – advanced wide field sensor, DEM – Digital Elevation Model, ETM – enhanced thematic mappter, FCC – False Color Composite, IRS – Indian Remote Sensing Satellite, LISS – linear imaging self sensor, MSS – multispectral sensor, OLI – operational land imager, PAN – panchromatic, SOI – Survey of India, SWIR – Short Wave Infrared, TM – thematic mapper, WiFS – wide field sensor.

3.3. *Mapping of debris cover glacier*

The presence of debris in Himalaya is commonly attributed to debris-laden ice avalanche and rockfall on glacier surface from steep surrounding slopes (Shroder et al. 2000). Previous studies (Paul et al. 2015, 2013) have reported errors involved in glacier mapping is minor due to the algorithm used when glaciers are heavily debris covered. Therefore, the presence of debris on the glacier has been recognized as a major constraint in glaciological studies (Paul et al. 2015; Shukla, Arora, and Gupta 2010). Mapping of debris-covered glaciers is important for the accurate determination of the spatial coverage of glaciers and for further applications which requires glacier area as an input component (Racoviteanu et al. 2009). The literature suggests that various studies have been carried out with a view to map debris cover glaciers using semi-automated or automated approach. Section (3.3.1–3.3.5) provides insight into significant semi-automated and automated techniques developed for debris cover delineation where studies carried out in other parts of the world (e.g. Andes and Alps) have also been referred to understand more vividly the recent advances in the domain. To highlight the crux of each of these techniques, they are classified into five categories viz. i) Supervised and unsupervised techniques, ii) Combination of multiple datasets, iii) ANN and CNN, iv) Object-Oriented Image Analysis and v) Others.

3.3.1. *Supervised and unsupervised classification techniques*

Generally, supervised classification has the following stages – training, feature selection, allocation and testing (Shukla, Gupta, and Arora 2009; Arora and Foody 1997). Supervised and unsupervised classification techniques are utilized by various studies to delineate glacier boundaries (Aniya et al. 1996; Bronge and Bronge†* 1999; Sidjak 1999; Shukla, Gupta, and Arora 2009). Here we have tabulated a (Table 3) the summary of some significant studies carried out with a view to delineate glacier boundary using supervised classification.

All studies discussed above have demonstrated the potential of supervised classification for glacial terrain mapping. Although the distinction between SGD and PGD remains a challenge as both have a similar spectral signature. Most of these studies (Table 3) applied classification scheme over the small geographical regions. However, this does not present the method as robust enough for fast and accurate glacier mapping. For the Indian Himalaya (Shukla, Gupta, and Arora 2009) showed the applicability of supervised classification for land cover classes in the glacial terrain in parts of Chenab basin using topographically corrected IRS-1C LISS III and IRS-P6 AWiFS remote sensing data. They used the Maximum likelihood classifier with standard FCC of B2, B4, B5 for supervised classification. A total of six land cover classes in the glacier terrain were reported, namely i) snow, ii) ice, iii) mixed ice and debris, iv) debris, v) valley rock, and vi) water. The study reports high (82% to 95%) accuracy for the above-mentioned techniques. However, the methodology failed to prove its robustness, as the researchers demonstrated this over a very small geographical region (e.g. <100 k^2). The study does not account for the complexity of glacial terrain (e.g. glacial lakes, shadow, cloud, and steep ice walls), these are not exclusively incorporated in this study.

3.3.2. *Combination of multiple datasets*

Owing to the spectral similarity between SGD and PGD, optical remote sensing is unable to distinguish between them. Hence, considering this particular aspect various studies

Table 3. Summary of some significant studies reported glacier delineation using supervised classification.

Location	Data Used*	Brief description	Reference
Southern Patagonia, ice field.	Landsat TM (30 m) FCC of TM 1, 4 and 5 bands were used for classification.	In addition aerial photography and topographic maps were used for identification of ice-divides. The study successfully demonstrates capabilities of supervised classification in estimation of glacier boundary and average accumulation area ratio.	(Aniya et al. 1996)
Vestfold Hills, East Antarctica.	Landsat TM (30 m)	In order to separate the major discernible feature of the ice this study demonstrates the applicability of maximum-likelihood classifier using the principal components as input data. This study reports ratio image (e.g. TM-3/TM-4) is a simple tool to distinguish between blue-ice and snow of various characters.	Bronge and Bronge (1999)
Illecillewaet British Columbia.	Landsat TM (30 m)	This study assesses the pertinence of maximum likelihood classifier using different input bands for mapping glacial extent. This study demonstrated that principal components analysis, image rationing and image differencing produce superior classification input channels compared to the original TM bands.	Sidjak (1999)

Note: *Values in the parenthesis is a spatial resolution of remote sensing sensor.
FCC – False Color Composite, TM – thematic mapper.

adopted a combination of datasets (e.g. Topographic, thermal and optical) to differentiate between SGD and PGD (Bhambri et al. 202011a11a, 2011b; Bhardwaj et al. 2014; Bishop et al. 2001; Bolch et al. 2007; Bolch and Kamp 2006; Bolch, Menounos, and Wheate 2010; Karimi et al. 2012; Paul, Huggel, and Kääb 2004; Ranzi et al. 2004; Shukla, Gupta, and Arora 2009; Shukla, Arora, and Gupta 2010; Taschner and Ranzi. 2002; Zollinger 2003). All of these studies took advantage of varied datasets (thermal band and geomorphometric parameter) in order to demarcate glacial boundary more precisely with a robust genetic interpretation. In order to understand the essence of each technique, we have discussed these one by one.

The work of (Bishop et al. 2001) demonstrated the capability of terrain characteristics for mapping glacier boundary and their results proved to be better while excluding the aspect. The study inferred that slope and aspect can be used for manual mapping of alpine glaciers. Overall the methodology of this study is promising. Nevertheless, it has several inaccuracies especially at the terminus; therefore the basic idea of Bishop et al. (2001) is also exploited by others. Taschner and Ranzi. (2002) heralded a new era of glacier mapping, as after several field observations their study successfully demonstrated thermal contrast between the ice-cored debris (SGD) and pure debris (PGD). To map glacier outline in Italian Alps clean ice was extracted using segmentation of ratio images aided with additional information on Normalized Difference Vegetation Index (NDVI). The thermal band was used to extract ice-cored debris pixels (SGD). However, the results could not exactly reproduce the information of reference data, especially the boundary at the terminus. After field investigation, they concluded that the presence of thick debris layer may act as an insulator for cooling ice which sets the limits for infrared radiometer to record thermal gap between ice-cored debris (SGD) and pure debris (PGD). Overall this study demonstrated the capabilities of the thermal band for demarcation of the boundary between ice-cored debris pixels and pure debris pixels. Further improvement in the spatial resolution of the thermal band could improve the classification accuracy. Ranzi et al. (2004) also investigated the temperature gap between ice-cored debris and pure debris for Belvedere Glacier. Field measurements and energy balance modelling manifest that the surface temperature of the debris layer superimposed over ice (SGD) are 4.5°C colder on average than debris present outside the glacier (PGD). The methodology adopted for glacier delineation in this study is quite similar to (Taschner and Ranzi. 2002) as clean ice was extracted with segmentation of ratio images. Further filters such as NDVI and thermal mask were used to narrow the fraction of candidated 'ice-cored debris' pixels. Finally, low pass and contextual filtering were applied considering the already detected glacier areas. This study emphasizes the temperature difference which exists between SGD and PGD over a large geographical region. These two studies laid the foundation for several other studies that have undertaken to map SGD and PGD on the basis of temperature difference. Although lower resolution of thermal band sets the limit for such an approach, both studies have shown uncertainty in results especially where thick debris is present and boundary between SGD and PGD was smooth. Even with such limits, both these studies have convincingly introduced the idea that significant temperature differences exist between SGD and PGD.

The study reported by Zollinger (2003) presented a multidimensional approach for mapping of debris cover glaciers in parts of the Mount Everest. It takes the advantage of multispectral classification, slope, and filters, similar to the previous studies that have shown the potential of multispectral image classification and morphometric characteristics for mapping debris cover glacier. The study by Paul, Huggel, and Andreas (2004) presented a semi-automated multisource approach for mapping debris cover glacier in parts of the Swiss Alps using Landsat data. This study was an attempt to integrate the advantages of multispectral remote sensing and DEM derived parameter (i.e. slope). Clean glacier ice and vegetation were extracted with automated multispectral classification whereas the debris cover was extracted with slope information (0–24°). Further neighbourhood-analysis was performed in order to improve the results (glacier/debris map). In such approaches threshold slope have to be used precisely. However, this study incorporated only one glacier as a test site (Figure 4(a)) and the accuracy of this method is dependent on some degree of manual correction. Consequently, the primary idea of the study could not be replicated. Bolch and Kamp (2006) followed a methodology which uses multispectral image analysis using segmentation of ratio images (TM4/TM5)

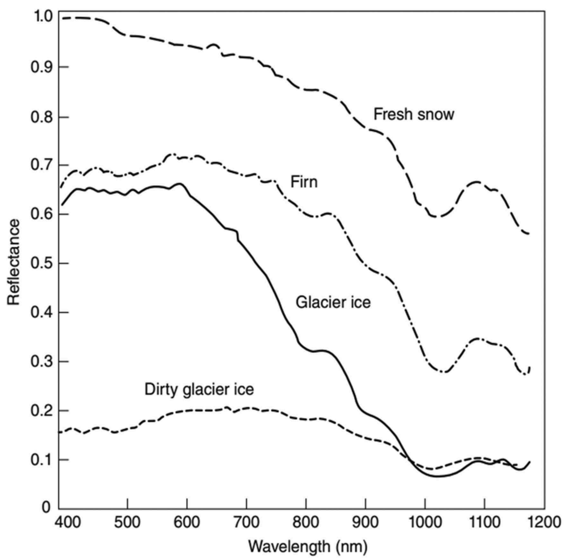

Figure 2. Reflectance spectra of different snow and ice surfaces (Hall and Martinec 1985).

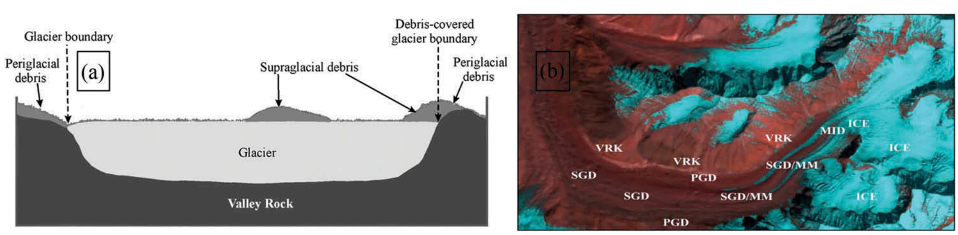

Figure 3. (a) Generalized cross-section of a typical valley glacier showing glacier boundary as a boundary between supraglacial and periglacial debris, figure courtesy of (Shukla, Arora, and Gupta 2010) (b) Shows the spectral similarity between supraglacial debris (SGD) and periglacial debris (PGD). VRK, valley rock; MID, mixed ice and debris.

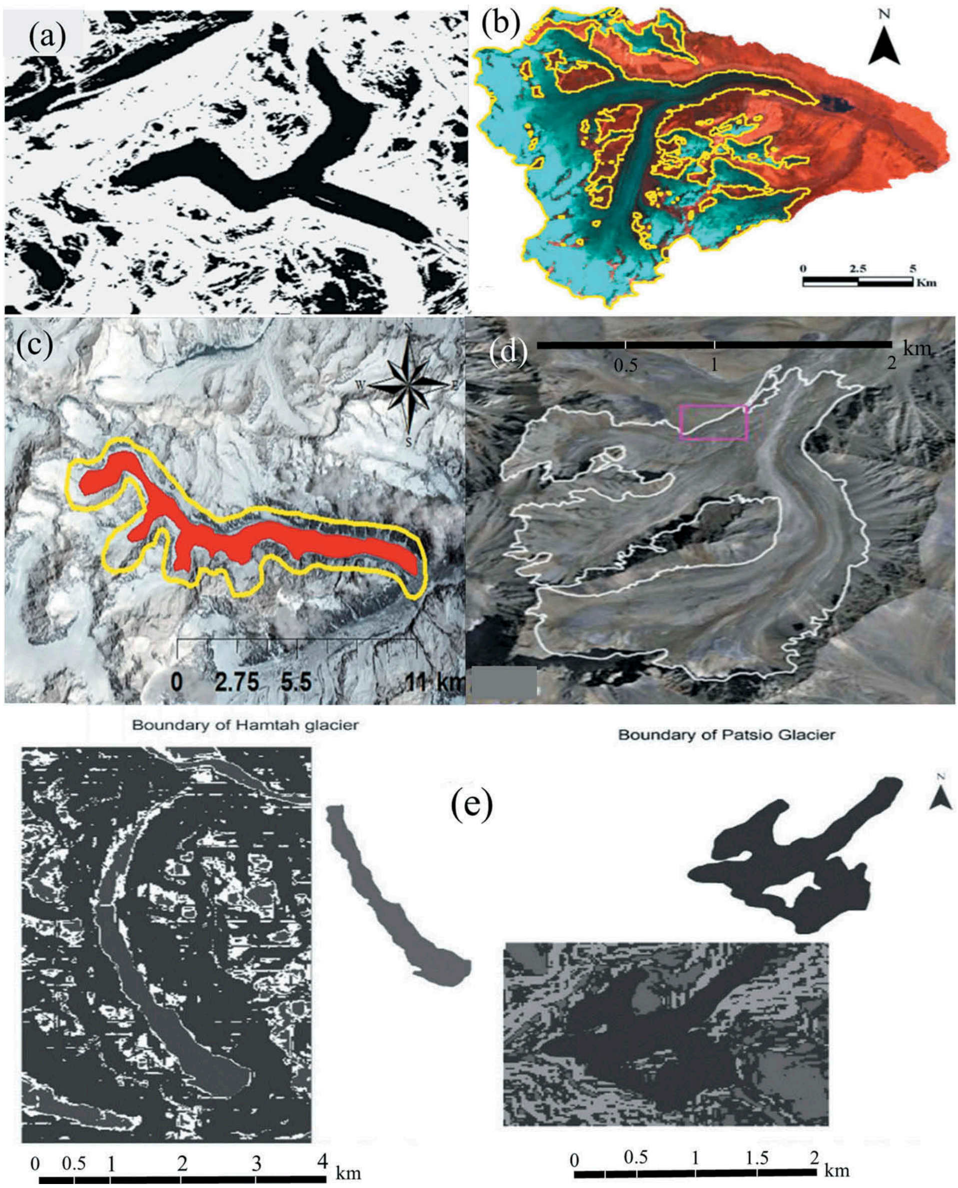

Figure 4. Results of some semi-automated approach for debris cover delineation using a combination of multiple dataset. (a) Debris cover glacier boundary delineated via semi-automated algorithms using multispectral imagery and DEM derived parameter (Paul, Huggel, and Andreas 2004), (b) Debris cover glacier boundary delineated using synergistic approach (Shukla, Arora, and Gupta 2010), (c) Glacier boundary extracted using hybrid CNN+ Radom forest (RF) approach (Nijhawan, Das, and Balasubramanian 2018), (d) Overlay of glacier boundary delineated using combination of optical and thermal data over high resolution satellite imagery (Karimi et al. 2012), (e) glacier boundary obtained via semi-automated approach, utilizing input from optical, thermal and surface curvature (Bhardwaj et al. 2014). This figure illustrates, most of the studies demonstrated a semi-automated approach for debris cover delineation on very small geographical area (i.e. 1or two glaciers) which reduces the involved complexity of glacial terrain.

followed by elimination of misclassified pixels from NDVI for delineation of clean ice. Further supra-glacial debris was mapped using morphometric glacier mapping (MGM) approach that focuses on curvature characteristics. However, this study explicitly stated that accuracy of the method is limited by on the resolution and quality of DEM and glacial surface features. This study demonstrates the potential of surface curvature for glacier mapping, which was further exploited by several studies.

The study reported by Bolch et al. (2007) takes the advantage of previous findings, e.g. (Paul, Huggel, and Andreas 2004; Taschner and Ranzi. 2002; Ranzi et al. 2004; Bolch and Kamp 2006) which showed the potential of morphometric parameters and thermal band for glacier mapping. This study demonstrated a novel automated approach for delineation of debris cover glacier boundary in parts of Nepal Himalaya, which combines ASTER thermal information with DEM derived parameters (e.g. slope gradient, plan curvature and profile curvature). However, the methodology is limited to the larger glaciers (e.g. Khumbu glacier, Nepal Himalaya) and major constraint of the methodology is the presence of stagnant ice present at the distal part which is even difficult to distinguish in the field. Bhambri et al. (2011b) demonstrated glacier fluctuation in the upper Bhagirathi and Saraswati/Alaknanda basins of the Garhwal Himalaya from 1968 to 2006. In order to study these changes researchers have adopted a modified classification scheme of the Global Land Ice Measurements from Space (GLIMS). First of all clean ice glacier is mapped using ratio image (NIR/SWIR) segmentation. Then, the misclassified pixels such as shadow, waterbodies, and isolated rocks are removed manually. Morphometric and thermal information is used to assist manual delineation of debris cover glaciers over ASTER imagery. Finally, the glacier boundary is established using high-resolution satellite data (e.g. Cartosat1 and LISS IV). This study also highlighted the enormous challenge posed by stagnant ice from active debris cover ice at the terminus.

(Shukla, Gupta, and Arora 2010) exploited a combination of optical and thermal remote sensing data using multispectral classification for a delineation of debris cover glacier in parts of Chenab basin, Himalaya. This study demonstrated the methodology on a very small geographical region (<100 km^2) which limits its robustness. As reproducibility of such work is quite low because lots of complexities may occur due to the heterogeneity of glacial terrain. Shukla, Arora, and Gupta (2010) followed a synergistic approach for glacier mapping in over same study region which utilizes the advantage of optical, thermal remote sensing data, multispectral classification along with DEM derived parameters. Overall this study made the first attempt to combine all these datasets for glacier mapping. This approach utilizes integrated optical and thermal datasets followed by multispectral classification and finally, the DEM derived parameters were used to evaluate the results. The study shows promising results when compared with reference dataset. However, the study incorporates very small geographical region as shown in Figure 4b, as a test site (i.e. one glacier) with multiple processing. Therefore, such approach has limited application for a fast and accurate glacier mapping over large geographical regions and cannot be considered as robust semi-automated method for glacier mapping in complex mountains terrain like Himalaya.

A similar approach is followed by Karimi et al. (2012) which uses Worldview-2, Landsat-TM (TIR band) and LiDAR data for delineation of Alamkouh glacier in Iran. Owing to the temperature difference in SGD and PGD, the glacier is segregated into a shaded and illuminated area. Thus, supervised classification was applied on shaded and illuminated part separately to map clean ice glacier and neural network classification was used to delineate debris cover part of the glacier. This study is similar to several previous studies that have already shown the potential of thermal and optical data for debris cover glacier mapping. Regardless of this, the study is limited by the applicability of the proposed approach over large geographical regions (Figure 4(d)). Bhardwaj et al. (2014) presented a semi-automated approach for mapping of debris cover glaciers, namely, Hamtah and Patsio located in the Himachal Himalaya. In their approach, supraglacial debris was extracted using a thermal mask and the extent of clean ice was generated using thresholding of ratio images. Further, a cluster analysis technique was used in order to rearrange the morphometric parameters (eg. slope, plan curvature, and profile curvature) and the glacier boundary was established using the GIS overlay operation based on spatial correspondence. The results of this approach match well with manually delineated glacier boundary. However, the study deals with only two glaciers of a relatively small geographical area as a test case (Figure 4 E) and so this methodology could not be taken as the generalized methodology for debris cover glacier mapping. Of course, the results are promising and better replication of such a methodology requires deeper analyses of datasets and precise modification in the thresholds.

3.3.3. *Object-oriented image analysis*

Recent advances in computer technology have led to the development of object-based image analysis (OBIA; (Blaschke 2001). The OBIA combines functionalities of older techniques of segmentation, edge detection, feature extraction in a GIS environment for extraction of information from remotely sensed data (Blaschke 2010). Working on the object-level facilitates with the combined use of spectral, spatial, textural and hierarchical properties makes this methodology promising for classification of remotely sensed data (Robson et al. 2015). OBIA also allows integration of multiple datasets (e.g. Optical, Thermal and DEM derived parameters) while working on near homogeneous objects. Therefore, several studies could successfully demonstrate the delineation of debris cover glaciers within in an object-based environment (Rastner et al. 2014; Bajracharya, Maharjan, and Shrestha 2014; Bajracharya and Shrestha 2011; Robson et al. 2015; Li, Bao, and Huang 2013; Biddle 2015; Jawak, Jadhav, and Luis 2016).

(Rastner et al. 2014) presented a comparative study of PBIA and OBIA for debris cover classification in three test regions, namely: Coasta Mountains of Canada, Watkin range of Greenland, and Nepal Himalaya. In both approaches, clean ice region was extracted using segmentation of ratio images while debris cover part was identified using temperature and slope threshold. The study demonstrates a slightly better accuracy of OBIA than PBIA. Unlike OBAI, the limitation of PBIA is mainly due to an error of commission which requires extensive post-processing. The OBIA has the advantage of post-processing (e.g. neighbourhood analysis and merging of all objects to relevant object) over PBIA which significantly improves the final classification. This study also infers that OBIA is more appropriate for mapping of large glaciers rather than small. The novelty of this approach lies in the comparison of OBIA and PBIA in three different test regions that implies a higher accuracy of OBIA over PBIA. However, the accuracy of OBIA is limited by the high spatial resolution of satellite imagery. The high-resolution data (<30 m) is required in order to map small glaciers and attain high accuracy. Glacier inventory of the Hindukush Himalaya (Bajracharya and Shrestha 2011) has been done using the semi-automated approach for delineation of clean ice (CI) and debris covered (DC) glacier using OBIA analysis. Clean ice glaciers were identified by applying the NDSI threshold based on the histogram, visual judgment, and sampling values. In order to remove any misclassified objects of shadow, waterbodies and bare rocks various filters were used (e.g. NDVI, hue, slope, and land-water mask (LWM)). Similarly, debris cover glaciers were extracted from the remaining unclassified image using slope and elevation thresholds. The results were refined using manual correction over high-resolution data. As this study applied the same methodology over the entire Hindu-Kush Himalaya and their results were consistent with previous studies. Hence, the replication of this approach is expected to yield better results. However, the amount of manual correction required is not known and need further work on this (Robson et al. 2015). Another study by Li, Bao, and Huang (2013) delineated full extent of debris cover glacier in the parts of eastern Tienshan Mountain using object image segmentation. This approach is also based on NDSI segmentation and terrain analysis in an object-based environment. The clouds and shadows are removed by merged multi-temporal images. The results of the presented methodology match well with the reference data that was prepared using manual delineation over high-resolution data (SPOT 5). However, the proposed methodology is challenged by the shadow and cloud identification whereas the complication related to the debris cover is not addressed by the researchers.

In recent studies (Frey, Paul, and Strozzi 2012; Robson et al. 2015; Saraswat et al. 2013) the potential of Synthetic Aperture Radar (SAR) for differentiating supra-glacial debris and peri-glacial debris have been exploited using coherence patterns between SAR images. Robson et al. (2015) reported an automated classification schema for debris cover glacier in parts of Mount Everest, Nepal Himalaya. They used OBIA capabilities for glacier mapping using optical, SAR coherence and topographic data. Their methodology provided an overall accuracy of 91% while it was 93% for clean ice and 83% for debris part. This novelty of the study lies in the fact that it attempts to address the problem over large geographical regions for fast and accurate glacier mapping. Moreover, the study exploits the capabilities of OBIA using SAR coherence, optical and topographic data which were not considered in earlier studies. One of the most striking features of the study is that it demonstrates the potential of SAR data in differentiating active ice from stagnant ice. Hitherto, this was a major challenge with the identification of stagnant ice present at distal part of the glacier. However, this methodology had some serious limitations such as steep slope valley, flowing surface water, rock slide, and vegetation. This methodology offers an implicitly robust way for mapping of large-scale heavy debris cover. Jawak, Jadhav, and Luis (2016) reported mapping of supraglacial debris in the Schirmacher Oasis, East Antarctica using high-resolution satellite data (e.g. WorldView-2). As the study has been carried out in a polar region, the challenges encountered were quite different from the Himalayan and any other mountainous region (i.e. differential amount of debris present and gentle topography as compared to mountainous region). The spectral properties of the debris in that region are very similar to that of blue ice or snow. However, the study reported supra-glacial debris extraction using object-oriented rule set and the results were extremely promising (~93% accuracy) as compared to traditional pixel-based classification (eg. supervised classification). As stated above the challenges confronted in this region are quite different from the Himalayan region. However, the study shows the potential of OBIA for mapping supraglacial debris using high spatial and spectral capabilities of WV-2 data.

3.3.4. *ANN and CNN approach*

Applicability of artificial neural network (ANN) classifier for estimation of debris over Himalayan glaciers is reported by several studies (Bishop, Shroder Jr, and Hickman 1999; Garg et al. 2017; Nijhawan, Das, and Balasubramanian 2018). Bishop, Shroder, and Hickman. (1999) demonstrated the utility of ANN for the identification of supraglacial debris in parts of Nanga Parbat, Pakistan using high-resolution satellite imagery (e.g. SPOT 5). This study incorporates a simple three-layer feed-forward network using the backpropagation learning algorithm for identifying spatial reflectance variation in the complex mountain environment. The results show that ANN outperformed the ISODATA algorithm. The results could be further improved by exploiting a larger training sample size. This study lays the foundation for ANN utilization in recognizing spatial reflectance variation in complex mountain terrain. Garg et al. (2017) reported supra-glacial debris classification using ANN in parts of Chandra basin, Himachal Himalaya. In order to extract supra-glacial debris well-defined and well-distributed training sets were used and the three-layer ANN model was iteratively optimized to find the most suitable parameters. However, the amount of manual correction applied at the post-processing stage made the interpretation of accuracy difficult.

More recently, deep learning has become popular among earth scientists and is applied to solve numerous outstanding research problems, including glacier mapping and characterization (Castelluccio et al. 2015). A study reported by Nijhawan, Das, and Balasubramanian (2018) demonstrates the novel hybrid deep learning framework approach for delineation of supra-glacial debris in parts of Alaknanda basin, Uttarakhand. Their presented approach utilizes multi-phase deep learning and random forest framework by the ensemble of CNN’s (CNN-A, CNN-B, and CNN-C). These use combinations of Landsat 8 multispectral bands, texture and topographic parameters as input. This study is novel in the sense that it uses deep learning algorithms for glacier classification. More work is required in order to apply it on large scale, as the authors could demonstrate its applicability over small scale (i.e. one glacier, <200 Km^2, Figure 4 (c)) for fast and accurate automated glacier mapping.

3.3.5. *Others*

This section highlights other significant techniques used for glacier mapping such as Decision Tree Algorithm (DTA), Texture Analysis (TA) and Hierarchical knowledge-based classification. Racoviteanu and Williams (2012) followed a comparative study of DTA and TA for mapping debris cover glacier in parts of eastern Himalaya. DTA classifies an image into classes by series of binary decisions. The researchers have used multispectral capabilities of ASTER (e.g. NDVI, NDSI, and hue), topographic characteristics (e.g. slope, elevation) and surface temperature to express condition with the threshold for DTA. Results of DTA were compared with debris cover outline extracted from a high-resolution imagery (e.g. quick bird) and a difference of 25% was found. However, this difference can be attributed to the difference in acquisition time of both datasets (e.g. ASTER-November 2001 and quickbird-January 2006). The study explicitly stated inaccuracies of the proposed methodology in areas of shadow, thick debris cover and cloud cover, which requires manual correction. On the other hand, results of the TA show a general agreement with DTA with a difference of 8% in areal extent. The followed approaches (e.g. DTA and TA) imply some serious limitation and challenges. As DTA requires extensive post-processing in order to obtain high accuracy. On the other hand, TA is limited by the fact that selected (ROIs) may not be the representative of all classes which leads to classification error. The essence of their study lies in the attempt to develop a methodology which can facilitate automated delineation of debris cover glacier in complex mountain terrain (i.e the Himalaya). The study reported by Shukla and Ali (2016) demonstrated a hierarchical knowledge-based classification (HKBC) approach for mapping of debris cover glacier in parts of Kashmir Himalaya using ASTER imagery and DEM. The proposed HKBC used several input layers from optical (e.g. NDSI, normalized-difference debris index (NDDI), Normalized-difference water index (NDWI)), topographic (e.g. slope) and thermal ASTER data. The results of the study (overall accuracy 89%) are promising and the researchers have argued that the results of HKBC are better than MLC and visual interpretation. However, without comparing the results obtained from HKBC with reference data (i.e. glacier boundary obtained from manual digitization over high-resolution data), it is difficult to agree with the authors claim. Moreover, the study does not incorporate a large geographical region as a test site, which limits the robustness of the proposed approach.

4. Discussion

4.1. *Existing approaches and emerging area of research*

The fast and accurate delineation of glacier boundary in the Himalayan region still remains a challenging task mainly due to the presence of supraglacial debris, perennial and/or seasonal snowfields, dead ice, shadow, identification of ice summit and clouds (Racoviteanu et al. 2009; Paul et al. 2013). Several authors (Aniya et al. 1996; Bajracharya and Shrestha 2011; Bishop, Shroder, and Hickman. 1999; Bishop, Shroder Jr, and Ward 1995; Bolch et al. 2007; Frey, Paul, and Strozzi 2012; Paul, Huggel, and Andreas 2004; Robson et al. 2015; Shukla, Arora, and Gupta 2010; Shukla, Gupta, and Arora 2010; Bhardwaj et al. 2014; Ranzi et al. 2004; Karimi et al. 2012) have adopted different techniques for semi-automated delineation of debris cover glacier viz. (ANN, Supervised classification, Integration of multiple data sets, CNN+RF, DTA and TA). However, the majority of these studies do not have the required accuracy and have relied to some degree of manual interpretation (Paul et al. 2015). The exact demarcation of glacier boundary can be difficult even using geophysical techniques in the field (Paul et al. 2015). Further, most of these studies are limited by their application over small geographical regions and only a small number of glaciers (<5) are analysed (Robson et al. 2015). This leaves outstanding issues and questions on their usage and applicability to larger regions. The basic idea behind most of these studies was the combination of several datasets (e.g. optical remote sensing data, topographic data, temperature data, and InSAR coherence data). The most promising results (96% and 91% accuracy) were reported by Nijhawan, Das, and Balasubramanian (2018), Robson et al. (2015) using novel hybrid deep learning framework approach and OBIA. However, except (Robson et al. 2015) none of them could achieve higher accuracy over large geographical regions.

Till date, there is no method devised which can facilitate higher accuracy over the large geographical region and reduced amount of cost, time and effort. Therefore, the development of algorithms which could facilitate fast and reliable glacier mapping is the need of the hour. The application of hybrid deep learning framework approach (e.g. CNN +Random forest approach) needs to be explored extensively. Moreover, potential of InSAR for glacier delineation require focused efforts. Previous studies have introduced the basic idea and its implementation over large regions is required.

The remarkable development in drone technology provides an efficient means to study mountain glacier (2018). UAVs helps to bridge the gap between field observations in a hostile environment and coarser-resolution satellite imagery (Immerzeel et al. 2014; Bhardwaj et al. 2016). Thereby, UAV based glaciological studies (2018; Fugazza et al. 2018; FUGAzzA et al. 2015; Immerzeel et al. 2014; Kraaijenbrink et al. 2016) are gaining pace in recent years as UAV have all the functionalities necessary for their practical applications for glaciological mapping and studies. UAVs have several advantages over conventional remote sensing platforms such as very high spatial resolution, capability to carry various types of payload and convenience in the choice of data acquisition period (Bhardwaj et al. 2016). UAVs datasets have numerous application in glaciology, single orthomosaics accompanied by DEM (2018) can be used to map glacial surface feature (i.e. debris, ice, and snout). Whereas time series data can facilitate quantification of surface flow velocity, glacier volume, snout elevation change and glacial hazards risk assessment (Kraaijenbrink et al. 2016; Immerzeel et al. 2014; Fugazza et al. 2018). The estimation of glacier flow velocity is typically limited by the pixel size of satellite imagery, as it is significantly larger than seasonal and even annual surface velocity of Himalayan debris-covered glaciers (Kraaijenbrink et al. 2016). Whereas, UAVs high resolution data can provide spatio-temporal variation in flow velocity, mass balance and spatial extent at a smaller scale. Thus, such comprehensive knowledge could provide insight into heterogeneous behaviour of Himalayan glaciers (Immerzeel et al. 2014).

There is no specific study which is dedicated to glacier mapping in Himalaya using UAV platform. Although several studies (Whitehead, Moorman, and Hugenholtz 2013; Whitehead 2013; Immerzeel et al. 2014; Miles et al. 2016; Kraaijenbrink et al. 2016) have shown the potential of UAVs in glaciological studies. Whitehead (2013) exploited the possible application of UAV's in glaciology and generated orthophotos of the terminus region of glacier to monitor the recent pattern of ice loss. For the first time (Immerzeel et al. 2014) used a UAV over the Himalaya. High-resolution ortho-mosaics and digital elevation models were prepared using stereo imaging and the structure from Motion (SfM) algorithm. The study reports surface velocity and mass loss of the glacier at a very high spatial accuracy. Moreover, the role of ponds and cliffs were discussed in detail in the overall melt of debris-covered terminus of Himalayan glaciers. This study provides a comprehensive picture of UAV's capabilities in glacier mapping and studies, as high-resolution DEM and high spatial resolution imagery can improve significantly the paradigm of glacier mapping. Similarly (Miles et al. 2016; Kraaijenbrink et al. 2016) used UAV platform in the Himalaya to study seasonal surface velocity of Lirung glacier, Nepal Himalaya and energy-balance modelling of Langtang Khola, Nepal Himalaya. The UAV's deployment in glaciology has shown great potential and this may further revolutionize the methods and approaches currently applied in studying glacier surface features. In general UAV imagery outweigh satellite-derived products in terms of resolution and accuracy, thereby deployment of UAV as a platform for glacier mapping and studies has tremendous potential and it may revolutionize the current state of glacier mapping.

4.2. *Errors associated with glacier mapping*

As the present focus is towards fast and accurate delineation of glaciers in the Himalaya, therefore evaluation of associated errors bears prime importance. Estimation of errors would help to draw a significant inference from the study. However, the detailed description of associated errors and guidelines for quality assessment have been the subject of recent studies (Paul et al. 2013, 2017). The major sources of error are (i) location error (GPS and geocoding), (ii) scene characteristics (e.g. presence of seasonal snow), (iii) sensor characteristics, (iv) DEM, (v) algorithm applied and (vi) interpretation error (Paul et al. 2017). Qualitative methods for determining uncertainty in glacier boundary is buffer method which is commonly used. In this method buffer equal to image registration error is created in and outside the glacier boundary (Granshaw and Fountain 2006). In the absence of reference datasets, multiple digitizations of selected glaciers with different geometry and estimating the standard deviation of digitization for accuracy assessment is recommended (Paul et al. 2013). As a measure of the quantitative method, the accuracy assessment of glacier boundary can be performed by comparison with reference datasets (Paul et al. 2017).

4.3. *Recommendations*

Over a large geographical region, semi-automated mapping of debris-cover glacier is advisable followed by finalization of glacier boundary manually using very high spatial resolution data. An integrated approach using surface slope, temperature, and SAR coherence has great potential in the mapping of debris-cover. Potential of machine learning algorithms (e.g. CNN and RF) and InSAR data need to be explored for automated glacier delineation as a step ahead towards the ongoing efforts. As one of the spectacular effects of global warming can be seen in the expansion and evolution of glacial lakes. The present efforts should be directed in utilizing such natural resources. Use of high-resolution DEM is not always advisable because of the noise in the data and the additional features that become visible. In such cases, terrain smoothing may be useful before applying the algorithms (Racoviteanu et al. 2009).

5. Conclusion

Finalization of the glacier boundary still depends largely on visual interpretation over high-resolution data, especially when higher accuracy is required. OBIA is quite useful while working with high or very high-resolution imagery, where an object of interest are usually larger than pixel size (Robson et al. 2015). Other than this, UAV's and SAR images have shown great potential for glacier mapping especially in rugged mountains such as the Himalaya. As a matter of emerging research area 'machine learning algorithms' are going to play a very significant role in near future, as the training of large sample size with multiple datasets (e.g optical, thermal, topographic and SAR) can improve present state of automated glaciers mapping. As a concluding remark, it is stated that glacier mapping has great significance in studying earth surface processes, understanding paleoclimate, impact of present climate, estimating and modelling the glacier dynamics and numerous other earth processes impacted by glacial dynamics. Therefore, accurate mapping of glaciers is imperative. So far several approaches and algorithms have shown potential for semi-automated delineation of debris cover glacier boundary; however, none of these have required accuracy. Further research is needed in this front, in order to develop a generalized semi-automated/automated algorithm or approach which can facilitate fast and accurate glacier mapping.

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References

Agarwal, N. K. 2001. "Remote Sensing for Glacier Mapping and Monitoring." *Geological Survey of India Special Publication* 53: 201–206.
Albert, T. H. 2002. "Evaluation of Remote Sensing Techniques for Ice-Area Classification Applied to the Tropical Quelccaya Ice Cap, Peru." *Polar Geography* 26 (3): 210–226. doi:10.1080/789610193.
Aniya, M., H. Sato, R. Naruse, P. Skvarca, and G. Casassa. 1996. "The Use of Satellite and Airborne Imagery to Inventory Outlet Glaciers of the Southern Patagonia Icefield, South America." *Photogrammetric Engineering and Remote Sensing* 62 (12): 1361–1369.
Arora, M. K., and G. M. Foody. 1997. "Log-Linear Modelling for the Evaluation of the Variables Affecting the Accuracy of Probabilistic, Fuzzy and Neural Network Classifications." *International Journal of Remote Sensing* 18 (4): 785–798. doi:10.1080/014311697218755.
Bahuguna, I. M. 2008. "Himalayan Glaciers." *ISG Newsletter* 14: 36–43.
Bahuguna, I. M., A. V. Kulkarni, S. Nayak, B. P. Rathore, H. S. Negi, and P. Mathur. 2007. "Himalayan Glacier Retreat Using IRS 1C PAN Stereo Data." *International Journal of Remote Sensing* 28 (2): 437–442. doi:10.1080/01431160500486674.
Bajracharya, S. R., and B. R. Shrestha. 2011. "The Status of Glaciers in the Hindu Kush-Himalayan Region." In *International Centre for Integrated Mountain Development (ICIMOD),* Nepal
Bajracharya, S. R., P. K. Mool, and B. R. Shrestha. 2007. *Impact of Climate Change on Himalayan Glaciers and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan*. Nepal: International Centre for Integrated Mountain Development (ICIMOD).

Bajracharya, S. R., S. B. Maharjan, and F. Shrestha. 2014. “The Status and Decadal Change of Glaciers in Bhutan from the 1980s to 2010 Based on Satellite Data.” *Annals of Glaciology* 55 (66): 159–166. doi:10.3189/2014AoG66A125.

Barry C. Bishop and Shiba P. Chatterjee, 2019. “Himalayas”. Encyclopaedia Britannica, inc. https://www.britannica.com/place/Himalayas

Basnett, Smriti, Anil V Kulkarni, and Tobias Bolch. 2013. “The Influence Of Debris Cover and Glacial Lakes on The Recession Of Glaciers in Sikkim Himalaya, India.” *Journal Of Glaciology* 59 (218): 1035-46.

Benoit, L., Gourdon, A., Vallat, R., Irarrazaval, I., Gravey, M., Lehmann, B., Prasicek, G., Gräff, D., Herman, F., and Mariethoz, G.: A high-frequency and high-resolution image time series of the Gornergletscher – Swiss Alps – derived from repeated UAV surveys, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-145, in review, 2018.

Bhambri, R., and T. Bolch. 2009. “Glacier Mapping: A Review with Special Reference to the Indian Himalayas.” *Progress in Physical Geography* 33 (5): 672–704. doi:10.1177/0309133309348112.

Bhambri, R., T. Bolch, and R. K. Chaujar. 2011a. “Mapping of Debris-Covered Glaciers in the Garhwal Himalayas Using ASTER DEMs and Thermal Data.” *International Journal of Remote Sensing* 32 (23): 8095–8119. doi:10.1080/01431161.2010.532821.

Bhambri, R., T. Bolch, R. K. Chaujar, and S. C. Kulshreshtha. 2011b. “Glacier Changes in the Garhwal Himalaya, India, from 1968 to 2006 Based on Remote Sensing.” *Journal of Glaciology* 57 (203): 543–556. doi:10.3189/002214311796905604.

Bhardwaj, A., L. Sam, F. Javier Martín-Torres, and R. Kumar. 2016. “UAVs as Remote Sensing Platform in Glaciology: Present Applications and Future Prospects.” *Remote Sensing of Environment* 175: 196–204. doi:10.1016/j.rse.2015.12.029.

Bhardwaj, A., M. K. Singh, P. K. Joshi, S. Singh, L. Sam, R. D. Gupta, and R. Kumar. 2015. “A Lake Detection Algorithm (LDA) Using Landsat 8 Data: A Comparative Approach in Glacial Environment.” *International Journal of Applied Earth Observation and Geoinformation* 38: 150–163. doi:10.1016/j.jag.2015.01.004.

Bhardwaj, A., P. K. Joshi, M. K. Singh, L. Sam, and R. D. Gupta. 2014. “Mapping Debris-Covered Glaciers and Identifying Factors Affecting the Accuracy.” *Cold Regions Science and Technology* 106: 161–174. doi:10.1016/j.coldregions.2014.07.006.

Biddle, D. J. 2015. *Mapping Debris-Covered Glaciers in the Cordillera Blanca, Peru: An Object-Based Image Analysis Approach*. Electronic Theses and Dissertations. Paper 2220. (Masters Dissertation, University of Louisville) https://doi.org/10.18297/etd/2220

Bishop, M. P., J. F. Shroder Jr, and B. L. Hickman. 1999. “SPOT Panchromatic Imagery and Neural Networks for Information Extraction in a Complex Mountain Environment.” *Geocarto International* 14 (2): 19–28. doi:10.1080/10106049908542100.

Bishop, M. P, John F Shroder Jr, and James L Ward. 1995. "SPOT multispectral analysis for producing supraglacial debris-load estimates for Batura glacier, Pakistan." Geocarto international https://doi.org/10.1080/10106049509354515.

Bishop, M. P., R. Bonk, U. Kamp Jr, and J. F. Shroder Jr. 2001. “Terrain Analysis and Data Modeling for Alpine Glacier Mapping.” *Polar Geography* 25 (3): 182–201. doi:10.1080/10889370109377712.

Blaschke, T. 2001. “What’s Wrong with Pixels? Some Recent Developments Interfacing Remote Sensing and GIS.” *GeoBIT/GIS* 6: 12–17.

Blaschke, T. 2010. “Object Based Image Analysis for Remote Sensing.” *ISPRS Journal of Photogrammetry and Remote Sensing* 65 (1): 2–16. doi:10.1016/j.isprsjprs.2009.06.004.

Bolch, T., B. Menounos, and R. Wheate. 2010. “Landsat-Based Inventory of Glaciers in Western Canada, 1985–2005.” *Remote Sensing of Environment* 114 (1): 127–137. doi:10.1016/j.rse.2009.08.015.

Bolch, T., M. F. Buchroithner, A. Kunert, and U. Kamp. 2007. “Automated Delineation of Debris-Covered Glaciers Based on ASTER Data.” *Paper presented at the Geoinformation in Europe. Proceedings of the 27th EARSeL Symposium,* Netherlands.

Bolch, T., and U. Kamp. 2006. “Glacier Mapping in High Mountains Using DEMs, Landsat and ASTER Data.” *Grazer Schriften der Geographie und Raumforschung* 41: 37–48.

Bronge, L. B., and C. Bronge †*. 1999. “Ice and Snow-Type Classification in the Vestfold Hills, East Antarctica, Using Landsat-TM Data and Ground Radiometer Measurements.” *International Journal of Remote Sensing* 20 (2): 225–240. doi:10.1080/014311699213415.

Brun, F., E. Berthier, P. Wagnon, A. Kääb, and D. Treichler. 2017. "A Spatially Resolved Estimate of High Mountain Asia Glacier Mass Balances from 2000 to 2016." *Nature Geoscience* 10 (9): 668–673. doi:10.1038/NGEO2999.

Castelluccio, M., G. Poggi, C. Sansone, and L. Verdoliva. 2015. Land use classification in remote sensing images by convolutional neural networks, arXiv preprint arXiv:1508.00092.

Chandler, B. M. P., H. Lovell, C. M. Boston, S. Lukas, L. D. Barr, Í. Ö. Benediktsson, D. I. Benn, C. D. Clark, C. M. Darvill, and D. J. A. Evans. 2018. "Glacial Geomorphological Mapping: A Review of Approaches and Frameworks for Best Practice." *Earth-Science Reviews,* 185: 806-846.

Conway, W. M. 1893. "The Crossing of the Hispar Pass." *The Geographical Journal* 1 (2): 131–138. doi:10.2307/1773755.

Dhanju, M. S., and A. Buch. 1989. "Remote Sensing of Himalayan Glaciers." *Proceedings of National Meet on Himalayan Glaciology*, New Delhi, 193–213.

Dobhal, D. P. 1992. "Inventory of Himachal Glaciers and Glaciological Studies of Chhota Shigri Glacier, Himachal Pradesh: A Case History." Ph. D. thesis of the Garhwal University, Srinagar.

Dobhal, D. P., and M. Mehta. 2010. "Surface Morphology, Elevation Changes and Terminus Retreat of Dokriani Glacier, Garhwal Himalaya: Implication for Climate Change." *Himalayan Geology* 31 (1): 71–78.

Dobhal, D. P., and S. Kumar. 1996. "Inventory of Glacier Basins in Himachal Himalaya." *Journal-Geological Society of India* 48: 671–682.

Dobhal, D. P., and S. Kumar. 1997. "Statistical Analysis of Glaciers in Himachal Pradesh, North-West Himalaya, India." *Current Science* 72 (5): 341–344.

Dobhal, D. P., S. Kumar, and A. K. Mundepi. 1995. "Morphology and Glacier Dynamics Studies in Monsoon–Arid Transition Zone: An Example from Chhota Shigri Glacier, Himachal-Himalaya, India." *Current Science* 68 (9): 936–944.

Dyhrenfurth, G. O. 2011. *To the Third Pole-The History of the High Himalaya*. Nielsen Press.

Frey, H., F. Paul, and T. Strozzi. 2012. "Compilation of a Glacier Inventory for the Western Himalayas from Satellite Data: Methods, Challenges, and Results." *Remote Sensing of Environment* 124: 832–843. doi:10.1016/j.rse.2012.06.020.

Fugazza, D., M. Scaioni, M. Corti, C. D'Agata, R. S. Azzoni, M. Cernuschi, C. Smiraglia, and G. A. Diolaiuti. 2018. "Combination of UAV and Terrestrial Photogrammetry to Assess Rapid Glacier Evolution and Map Glacier Hazards." *Natural Hazards and Earth System Sciences* 18 (4): 1055–1071. doi:10.5194/nhess-18-1055-2018.

Fugazza, D. A. V. I. D. E., A. N. T. O. N. E. L. L. A. SeNeSe, R. O. B. E. R. T. O. SERGIO AzzONI, C. Smiraglia, M. A. S. S. I. M. O. CeRNUSCHI, D. A. V. I. D. E. SeVeRI, and G. A. Diolaiuti. 2015. "High-Resolution Mapping of Glacier Surface Features. The UAV Survey of the Forni Glacier (Stelvio National Park, Italy)."

Gao, J., and Y. Liu. 2001. "Applications of Remote Sensing, GIS and GPS in Glaciology: A Review." *Progress in Physical Geography* 25 (4): 520–540. doi:10.1177/030913330102500404.

Garg, P. K., A. Shukla, R. K. Tiwari, and A. S. Jasrotia. 2017. "Assessing the Status of Glaciers in Part of the Chandra Basin, Himachal Himalaya: A Multiparametric Approach." *Geomorphology* 284: 99–114. doi:10.1016/j.geomorph.2016.10.022.

Gilbert, L. B., and J. B. Auden. 1935. "Note on a Glacier in the Arwa Valley, British Garhwal." *Records of Geological Survey of India* 66: 388–404.

Godwin-Austen, H. H. 1864. "On the Glaciers of the Mustakh Range." *The Journal of the Royal Geographical Society of London* 34: 19–56. doi:10.2307/1798464.

Granshaw, F. D., and A. G. Fountain. 2006. "Glacier Change (1958–1998) in the North Cascades National Park Complex, Washington, USA." *Journal of Glaciology* 52 (177): 251–256. doi:10.3189/172756506781828782.

Hall, D.K., and J. Martinec. 1985. "Remote Sensing of Ice and Snow". Chapman and Hall Ltd. London

Hodgson, J.A. 1822. *Journal of a Survey to the Heads of the Rivers Ganges and Jumna*. Asiatic Research, 14, 60-152.

Immerzeel, W. W., P. D. A. Kraaijenbrink, J. M. Shea, A. B. Shrestha, F. Pellicciotti, M. F. P. Bierkens, and S. M. De Jong. 2014. "High-Resolution Monitoring of Himalayan Glacier Dynamics Using Unmanned Aerial Vehicles." *Remote Sensing of Environment* 150: 93–103. doi:10.1016/j.rse.2014.04.025.

Jawak, S. D., A. Jadhav, and A. J. Luis. 2016. “Object-Oriented Feature Extraction Approach for Mapping Supraglacial Debris in Schirmacher Oasis Using Very High-Resolution Satellite Data.” Paper presented at the land surface and cryosphere remote sensing III.
Kääb, A., C. Huggel, F. Paul, R. Wessels, B. Raup, H. Kieffer, and J. Kargel. 2002. “Glacier Monitoring from ASTER Imagery: Accuracy and Applications.” Paper presented at the Proceedings of EARSeL-LISSIG-Workshop observing our cryosphere from Space.
Kääb, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud. 2012. “Contrasting Patterns of Early Twenty-First-Century Glacier Mass Change in the Himalayas.” *Nature* 488 (7412): 495. doi:10.1038/nature11324.
Karimi, N., A. Farokhnia, L. Karimi, M. Eftekhari, and H. Ghalkhani. 2012. “Combining Optical and Thermal Remote Sensing Data for Mapping Debris-Covered Glaciers (Alamkouh Glaciers, Iran).” *Cold Regions Science and Technology* 71: 73–83. doi:10.1016/j.coldregions.2011.10.004.
Kaul, M. K. 1999. “Inventory of the Himalayan Glaciers.” Contribution to the International Hydrological Programme. Geological Survey of India Special Publication No.34, 165p.
Kaushik, S., J. K. Dharpure, P. K. Joshi, A. L. Ramanathan, and T. Singh. 2018. “Climate Change Drives Glacier Retreat in Bhaga Basin Located in Himachal Pradesh, India.” *Geocarto International*. https://doi.org/10.1080/10106049.2018.1557260
Kraaijenbrink, P., S. W. Meijer, J. M. Shea, F. Pellicciotti, S. M. De Jong, and W. W. Immerzeel. 2016. “Seasonal Surface Velocities of a Himalayan Glacier Derived by Automated Correlation of Unmanned Aerial Vehicle Imagery.” *Annals of Glaciology* 57 (71): 103–113. doi:10.3189/2016AoG71A072.
Krishna, A. P. 2005. “Snow and Glacier Cover Assessment in the High Mountains of Sikkim Himalaya.” *Hydrological Processes* 19 (12): 2375–2383. doi:10.1002/hyp.5890.
Kulkarni, A. V. 1991. “Glacier Inventory in Himachal Pradesh Using Satellite Images.” *Journal of the Indian Society of Remote Sensing* 19 (3): 195–203. doi:10.1007/BF03030771.
Kulkarni, A. V. 1993. "A remote sensing based glacier inventory and mass balance study in the parts of Chandra river basin Himachal Pradesh." Phd thesis submitted to Shivaji university http://hdl.handle.net/10603/140684.
Kulkarni, A. V. 2007. “Effect of Global Warming on the Himalayan Cryosphere.” *Jalvigyan Sameeksha* 22: 93–108.
Kulkarni, A. V., and A. M. Buch. 1991. *Glacier Atlas of Indian Himalaya*. Ahmedabad: Space Application Centre (ISRO).
Kulkarni, A. V., B. P. Rathore, S. Mahajan, and P. Mathur. 2005. “Alarming Retreat of Parbati Glacier, Beas Basin, Himachal Pradesh.” *Current Science* 88 (11): 1844–1850.
Kulkarni, A. V., B. P. Rathore, S. K. Singh, and I. M. Bahuguna. 2011. “Understanding Changes in the Himalayan Cryosphere Using Remote Sensing Techniques.” *International Journal of Remote Sensing* 32 (3): 601–615. doi:10.1080/01431161.2010.517802.
Kulkarni, A. V., G. Philip, V. C. Thakur, R. K. Sood, S. S. Randhawa, and R. Chandra. 1999. “Glacier Inventory of the Satluj Basin Using Remote Sensing Technique.” *Himalayan Geology* 20 (2): 45–52.
Kulkarni, A. V., I. M. Bahuguna, B. P. Rathore, S. K. Singh, S. S. Randhawa, R. K. Sood, and S. Dhar. 2007. “Glacial Retreat in Himalaya Using Indian Remote Sensing Satellite Data.” *Current Science* 92 (1): 69–74.
Kulkarni, A. V., P. Mathur, B. P. Rathore, S. Alex, N. Thakur, and M. Kumar. 2002. “Effect of Global Warming on Snow Ablation Pattern in the Himalaya.” *Current Science* 83 (2): 120–123.
Kulkarni, Anil V, and Suja Alex. 2003. “Estimation Of Recent Glacial Variations in Baspa Basin Using Remote Sensing Technique.” *Journal Of The Indian Society Of Remote Sensing* 31 (2): 81. doi:.
Kulkarni, Anil V, Sunil Dhar, BP Rathore, and Rajeev Kalia. 2006. “Recession Of Samudra Tapu Glacier, Chandra River Basin, Himachal Pradesh.” *Journal Of The Indian Society Of Remote Sensing* 34 (1): 39-46.
Kumar, S., and D. P. Dobhal. 1994. “Snout Fluctuation Study of Chhota-Shigri Glacier Lahaul and Spiti District, Himachal-Pradesh.” *Journal of the Geological Society of India* 44 (5): 581–585.
Kumar, V., G. Venkataramana, and K. A. Høgda. 2011. “Glacier Surface Velocity Estimation Using SAR Interferometry Technique Applying Ascending and Descending Passes in Himalayas.”

International Journal of Applied Earth Observation and Geoinformation 13 (4): 545–551. doi:10.1016/j.jag.2011.02.004.

Li, J. L., A. M. Bao, and Q. T. Huang. 2013. "A Object-Oriented Glacier Mapping Method Based on Multi-Temporal Landsat Images." Paper presented at the MIPPR 2013: Remote sensing image processing, Geographic information systems, and other applications.

Li, W., D. Zhiqiang, F. Ling, D. Zhou, H. Wang, Y. Gui, B. Sun, and X. Zhang. 2013b. "A Comparison of Land Surface Water Mapping Using the Normalized Difference Water Index from TM, ETM+ and ALI." *Remote Sensing* 5 (11): 5530–5549. doi:10.3390/rs5115530.

Longstaff, T. G. 1908. "A Mountaineering Expedition to the Himalaya of Garhwal." *The Geographical Journal* 31 (4): 361–388. doi:10.2307/1777841.

Mason, K. 1927. "The Shaksgam Valley and Aghil Range." *The Geographical Journal* 69 (4): 289–323. doi:10.2307/1782759.

Mason, K. 1929. *The Representation of Glaciated Regions on Maps of the Survey of India*. Professional Paper 25. Dehradun: Geodetic Branch, Survey of India, 18 pp.

Mason, K. 1930. *The Glaciers of the Karakoram and Neighbourhood*. Records of the Geological Survey of India, 63(2), 214–278.

Mayewski, P. A., and P. A. Jeschke. 1979. "Himalayan and Trans-Himalayan Glacier Fluctuations since AD 1812." *Arctic and Alpine Research* 11 (3): 267–287. doi:10.2307/1550417.

Mercer, J. H. 1963. "Glacier Variations in the Karakoram." *Glaciological Notes* 14: 19–33.

Miles, E. S., F. Pellicciotti, I. C. Willis, J. F. Steiner, P. Buri, and N. S. Arnold. 2016. "Refined Energy-Balance Modelling of a Supraglacial Pond, Langtang Khola, Nepal." *Annals of Glaciology* 57 (71): 29–40. doi:10.3189/2016AoG71A421.

Miller, P. E., M. Kunz, J. P. Mills, M. A. King, T. Murray, T. D. James, and S. H. Marsh. 2009. "Assessment of Glacier Volume Change Using ASTER-based Surface Matching of Historical Photography." *IEEE Transactions on Geoscience and Remote Sensing* 47 (7): 1971–1979. doi:10.1109/TGRS.2009.2012702.

Mourya, D. T., P. V. Barde, M. D. Gokhale, A. C. Mishra, V. S. Padbidri, P. CYRIL JAYKUMAR, and Y. Shouche. 2002. "Effect of Global Warming on Snow Ablation Pattern in the Himalaya." *Current Science* 83 (2): 120.

Mukherjee, K., A. Bhattacharya, T. Pieczonka, S. Ghosh, and T. Bolch. 2018. "Glacier Mass Budget and Climate Reanalysis Data Indicate a Climatic Shift around 2000 in Lahaul-Spiti, Western Himalaya." *Climatic Change* 148 (1–2): 219–233. doi:10.1007/s10584-018-2185-3.

Murtaza, Khalid Omar, and Shakil A Romshoo. 2017. "Recent Glacier Changes in The Kashmir Alpine Himalayas, India." *Geocarto International* 32 (2): 188-205.

Nijhawan, R., J. Das, and R. Balasubramanian. 2018. "A Hybrid CNN+ Random Forest Approach to Delineate Debris Covered Glaciers Using Deep Features." *Journal of the Indian Society of RemoteSensing* 46 (6): 1–9.

Nuimura, T, A Sakai, K Taniguchi, H Nagai, D Lamsal, S Tsutaki, A Kozawa, Y Hoshina, S Takenaka, and S Omiya. 2015. "The Gamdam Glacier Inventory: a Quality-controlled Inventory Of Asian Glaciers." *Cryosphere* 9: 3.

Oerlemans, J. 2005. "Extracting a Climate Signal from 169 Glacier Records." *Science* 308 (5722): 675–677. doi:10.1126/science.1107046.

Pandey, P., and G. Venkataraman. 2013. "Changes in the Glaciers of Chandra–Bhaga Basin, Himachal Himalaya, India, between 1980 and 2010 Measured Using Remote Sensing." *International Journal of Remote Sensing* 34 (15): 5584–5597. doi:10.1080/01431161.2013.793464.

Paul, F., A. Kääb, and W. Haeberli. 2007. "Recent Glacier Changes in the Alps Observed by Satellite: Consequences for Future Monitoring Strategies." *Global and Planetary Change* 56 (1–2): 111–122. doi:10.1016/j.gloplacha.2006.07.007.

Paul, F., C. Huggel, and K. Andreas. 2004. "Combining Satellite Multispectral Image Data and a Digital Elevation Model for Mapping Debris-Covered Glaciers." *Remote Sensing of Environment* 89 (4): 510–518. doi:10.1016/j.rse.2003.11.007.

Paul, F., and K. Andreas. 2005. "Perspectives on the Production of a Glacier Inventory from Multispectral Satellite Data in Arctic Canada: Cumberland Peninsula, Baffin Island." *Annals of Glaciology* 42: 59–66. doi:10.3189/172756405781813087.

Paul, F., N. E. Barrand, S. Baumann, E. Berthier, T. Bolch, K. Casey, H. Frey, S. P. Joshi, V. Konovalov, and L. B. Raymond. 2013. "On the Accuracy of Glacier Outlines Derived from Remote-Sensing Data." *Annals of Glaciology* 54 (63): 171–182. doi:10.3189/2013AoG63A296.

Paul, F., T. Bolch, A. Kääb, T. Nagler, C. Nuth, K. Scharrer, A. Shepherd, T. Strozzi, F. Ticconi, and R. Bhambri. 2015. "The Glaciers Climate Change Initiative: Methods for Creating Glacier Area, Elevation Change and Velocity Products." *Remote Sensing of Environment* 162: 408–426. doi:10.1016/j.rse.2013.07.043.

Paul, F., T. Bolch, K. Briggs, A. Kääb, M. McMillan, R. McNabb, T. Nagler, C. Nuth, P. Rastner, and T. Strozzi. 2017. "Error Sources and Guidelines for Quality Assessment of Glacier Area, Elevation Change, and Velocity Products Derived from Satellite Data in the Glaciers_Cci Project." *Remote Sensing of Environment* 203: 256–275. doi:10.1016/j.rse.2017.08.038.

Rabatel, A., A. Letréguilly, J. P. Dedieu, and N. Eckert. 2013. "Changes in Glacier Equilibrium-Line Altitude in the Western Alps from 1984 to 2010: Evaluation by Remote Sensing and Modeling of the Morpho-Topographic and Climate Controls." *The Cryosphere* 7 (5): 1455–1471. doi:10.5194/tc-7-1455-2013.

Rabatel, A., J.-P. Dedieu, and C. Vincent. 2005. "Using Remote-Sensing Data to Determine Equilibrium-Line Altitude and Mass-Balance Time Series: Validation on Three French Glaciers, 1994–2002." *Journal of Glaciology* 51 (175): 539–546. doi:10.3189/172756505781829106.

Racoviteanu, A., and M. W. Williams. 2012. "Decision Tree and Texture Analysis for Mapping Debris-Covered Glaciers in the Kangchenjunga Area, Eastern Himalaya." *Remote Sensing* 4 (10): 3078–3109. doi:10.3390/rs4103078.

Racoviteanu, A. E., F. Paul, B. Raup, S. J. Singh Khalsa, and R. Armstrong. 2009. "Challenges and Recommendations in Mapping of Glacier Parameters from Space: Results of the 2008 Global Land Ice Measurements from Space (GLIMS) Workshop, Boulder, Colorado, USA." *Annals of Glaciology* 50 (53): 53–69. doi:10.3189/172756410790595804.

Racoviteanu, A. E. Y. Arnaud, M. W. Williams, and W. F. Manley. 2014. "Spatial Patterns in Glacier Characteristics and Area Changes from 1962 to 2006 in The Kanchenjunga¨csikkim Area, Eastern Himalaya." *The Cryosphere* 9: 505-23. doi:.

Raina, V. K. 2009. Himalayan glaciers: A state-of-art review of glacial studies, glacial retreat and climate change. p 60 (discussion paper, Ministry of Environment and Forests, Government of India, New Delhi).

Raina, V. K., and D. Srivastava. 2008. "Glacier Atlas of India, Bangalore." *Geological Society of India*, 316.

Rankl, M., and M. Braun. 2016. "Glacier Elevation and Mass Changes over the Central Karakoram Region Estimated from TanDEM-X and SRTM/X-SAR Digital Elevation Models." *Annals of Glaciology* 57 (71): 273–281. doi:10.3189/2016AoG71A024.

Ranzi, R., G. Grossi, L. Iacovelli, and S. Taschner. 2004. "Use of Multispectral ASTER Images for Mapping Debris-Covered Glaciers within the GLIMS Project." Paper presented at the Geoscience and Remote Sensing Symposium, 2004. IGARSS'04. Proceedings, 2004 IEEE International.

Rao, Y. S., G. Venkataraman, and K. S. Rao. 2004. "SAR Interferometry for DEM Generation and Movemnet of Indian Glaciers." Paper presented at the Geoscience and Remote Sensing Symposium, 2004. IGARSS'04. Proceedings, 2004 IEEE International.

Rastner, P., T. Bolch, C. Notarnicola, and F. Paul. 2014. "A Comparison of Pixel-And Object-Based Glacier Classification with Optical Satellite Images." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 7 (3): 853–862. doi:10.1109/JSTARS.2013.2274668.

Robson, B. A., C. Nuth, S. O. Dahl, D. Hölbling, T. Strozzi, and P. R. Nielsen. 2015. "Automated Classification of Debris-Covered Glaciers Combining Optical, SAR and Topographic Data in an Object-Based Environment." *Remote Sensing of Environment* 170: 372–387. doi:10.1016/j.rse.2015.10.001.

Sangewar, C. V. 2012. "Remote Sensing Applications to Study Indian Glaciers." *Geocarto International* 27 (3): 197–206. doi:10.1080/10106049.2011.617841.

Saraswat, P., T. H. Syed, J. S. Famiglietti, E. J. Fielding, R. Crippen, and N. Gupta. 2013. "Recent Changes in the Snout Position and Surface Velocity of Gangotri Glacier Observed from Space." *International Journal of Remote Sensing* 34 (24): 8653–8668. doi:10.1080/01431161.2013.845923.

Satyabala, S. P. 2016. “Spatiotemporal Variations in Surface Velocity of the Gangotri Glacier, Garhwal Himalaya, India: Study Using Synthetic Aperture Radar Data.” *Remote Sensing of Environment* 181: 151–161. doi:10.1016/j.rse.2016.03.042.

Scherler, D., S. Leprince, and M. R. Strecker. 2008. “Glacier-Surface Velocities in Alpine Terrain from Optical Satellite imagery—Accuracy Improvement and Quality Assessment.” *Remote Sensing of Environment* 112 (10): 3806–3819. doi:10.1016/j.rse.2008.05.018.

Shangguan, D., S. Liu, Y. Ding, L. Ding, L. Xiong, D. Cai, L. Gang, L. Anxin, S. Zhang, and Y. Zhang. 2006. “Monitoring the Glacier Changes in the Muztag Ata and Konggur Mountains, East Pamirs, Based on Chinese Glacier Inventory and Recent Satellite Imagery.” *Annals of Glaciology* 43: 79–85. doi:10.3189/172756406781812393.

Shipton, E., M. Spender, and J. B. Auden. 1938. “The Shaksgam Expedition, 1937.” *The Geographical Journal* 91 (4): 313–336. doi:10.2307/1788187.

Shroder, J. F., M. P. Bishop, L. Copland, and V. F. Sloan. 2000. “Debris-Covered Glaciers and Rock Glaciers in the Nanga Parbat Himalaya, Pakistan.” *Geografiska Annaler* 82 (1): 17–31. doi:10.1111/j.0435-3676.2000.00108.x.

Shukla, A. 2009. "REMOTE SENSING BASED GLACIER TERRAIN MAPPING IN PARTS OF CHENAB BASIN, HIMALAYA." (Doctoral dissertation, Indian Institute of Technology, Roorkee, India).

Shukla, A., and I. Ali. 2016. “A Hierarchical Knowledge-Based Classification for Glacier Terrain Mapping: A Case Study from Kolahoi Glacier, Kashmir Himalaya.” *Annals of Glaciology* 57 (71): 1–10. doi:10.3189/2016AoG71A046.

Shukla, A., M. K. Arora, and R. P. Gupta. 2010. “Synergistic Approach for Mapping Debris-Covered Glaciers Using Optical–Thermal Remote Sensing Data with Inputs from Geomorphometric Parameters.” *Remote Sensing of Environment* 114 (7): 1378–1387. doi:10.1016/j.rse.2010.01.015.

Shukla, A., R. P. Gupta, and M. K. Arora. 2009. “Estimation of Debris Cover and Its Temporal Variation Using Optical Satellite Sensor Data: A Case Study in Chenab Basin, Himalaya.” *Journal of Glaciology* 55 (191): 444–452. doi:10.3189/002214309788816632.

Shukla, A., R. P. Gupta, and M. K. Arora. 2010. “Delineation of Debris-Covered Glacier Boundaries Using Optical and Thermal Remote Sensing Data.” *Remote Sensing Letters* 1 (1): 11–17. doi:10.1080/01431160903159316.

Sidjak, R. W. 1999. “Glacier Mapping of the Illecillewaet Icefield, British Columbia, Canada, Using Landsat TM and Digital Elevation Data.” *International Journal of Remote Sensing* 20 (2): 273–284. doi:10.1080/014311699213442.

Surazakov, A. B., and V. B. Aizen. 2006. “Estimating Volume Change of Mountain Glaciers Using SRTM and Map-Based Topographic Data.” *IEEE Transactions on Geoscience and Remote Sensing* 44 (10): 2991–2995. doi:10.1109/TGRS.2006.875357.

Taschner, S., and R. Ranzi. 2002. “Comparing the Opportunities of Landsat-TM and Aster Data for Monitoring a Debris Covered Glacier in the Italian Alps within the GLIMS Project”. Paper presented at the Geoscience and Remote Sensing Symposium, 2002. IGARSS’02. 2002 IEEE International. doi:10.1044/1059-0889(2002/er01)

Tewari, A. P. 1971. “A Short Report on Glacier Studies in the Himalayan Mountains by the Geological Survey of India.” *Stud Geomorph Carpatho-Balcanica* 5: 173–181.

Thakuri, S., F. Salerno, C. Smiraglia, T. Bolch, C. D’Agata, G. Viviano, and G. Tartari. 2014. “Tracing Glacier Changes since the 1960s on the South Slope of Mt. Everest (Central Southern Himalaya) Using Optical Satellite Imagery.” *Global and Planetary Change* 8 (4): 1297–1315.

Ullah, M. I. 1843. “Travels beyond the Himalaya.” *Journal of the Royal Asiatic Society of Great Britain and Ireland* 7 (2): 283–342. doi:10.1017/S0035869X00155947.

Visser, P. C. 1926. “Explorations in the Karakoram.” *Geographical Journal* 457–468. doi:10.2307/1782001.

Visser, P. C., and J. Visser-Hooft. 1938. *Karakoram: Wissenschaftliche Ergebnisse der Niederlandischen Expeditionen in den Karakorum und die angrenzenden Gebiete in den Jahren 1922, 1925, 1929/30 und 1935*. Leiden: EJ Brill.

Vohra, C. P. 1980. “Some Problems of Glacier Inventory in the Himalayas.” *IAHS Publ* 126: 67–74.

Whitehead, K., B. J. Moorman, and C. H. Hugenholtz. 2013. “Brief Communication: Low-Cost, On-Demand Aerial Photogrammetry for Glaciological Measurement.” *The Cryosphere* 7 (6): 1879–1884. doi:10.5194/tc-7-1879-2013.

Whitehead, K. L. 2013. "An integrated approach to determining short-term and long-term patterns of surface change and flow characteristics for a polythermal arctic g(Doctoral dissertation, University of Calgary).

Zollinger, S. 2003. “Ableitung von Parametern für die Identifikation und Beobachtung gefährlicher Gletscherseen in Nepal aus ASTER Satellitendaten.” Verlag nicht ermittelbar.